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RESEARCH ARTICLES

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Abstract Recent research almost unambiguously refutes the hypothesis that the timing of interceptive actions is solely based on the relative rate of expansion [i.e. $\tau(\varphi)$]. The aim of the present experiment was to evaluated the merits of eight alternative informational variables that recently have been proposed in the literature $\left(\text{i.e. } \dot{\varphi}, \dot{\theta}, \dot{\Delta}, \tau(\varphi), \tau(\theta), \tau(\Delta), \tau(\varphi,\theta), \zeta\right)$. Participants ($n$=7) were required to regulate the spatio-temporal characteristics of their reach and grasp to catch a ball approaching on a constant spatial trajectory. To identify the information used to regulate the timing of the catch we examined the qualitative effects of ball speed (0.5, 1.0, 1.5, 2.0, and 2.5 m/s) and viewing (monocular versus binocular) on the kinematics of the catch. Subsequently, we directly assessed the quantitative relationship between informational variables and the timing of reach onset and hand closure. The findings raised serious doubts against the use of variables that specified the time-to-contact between the ball and the point of observation (i.e. relative rate of expansion and disparity). Further, optical variables solely confined to the trajectory of the ball (i.e. the absolute rate of expansion) did yield positive results for the timing of reach onset but not for the timing of hand closure. Only variables that were related to the closure of the gap between hand and ball were found to contribute to the timing of hand closure. These results suggest that information related to the constriction of the optical gap between end-effector and ball becomes more important with approach, whereas the contribution of the absolute rate of expansion becomes less leading.

Keywords Optical variables · Timing · Catching · Vision · Human

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Introduction

An important aspect of interceptive actions is the precision with which actions are timed. To temporally coordinate the effector movement with the movement of the ball an actor needs optical information. The aim of the present paper is to identify the optical information that is used to time the initiation of interceptive actions, such as catching. For many years, it was established that an organism–environment property of particular importance is the time remaining before the ball reaches the actor. Lee (1976; for earlier accounts see also Knowles and Carel 1958; Purdy 1958) mathematically derived that, given a constant approach velocity, the inverse of the relative rate of optical expansion [i.e. $\tau(\varphi)$], directly specifies time-to-contact (TTC) with the point of observation [1]. Following Lee's seminal article, empirical evidence was interpreted as certifying that $\tau(\varphi)$ is the only source of TTC information and, as such, is used by various species to regulate the interception or avoidance of approaching objects (e.g. Lee and Reddish 1981, Lee et al. 1983; Savelsbergh et al.

[1] $$\tau(\varphi) = \frac{\varphi}{\dot{\varphi}} \approx \frac{X}{\dot{X}} = TTC_1$$

where X is an organism–environment property (i.e. distance between object and observer), which together with its first time-derivative defines TTC. The subscript 1 indicates that only the first-order time-derivative of X is considered. For small angles of (e.g. the angle subtended by the edges of the object and the point of observation) the organism–environment property TTC_1 is specified by the optical variable ().

1991, 1992). Unfortunately, the validity of these studies in testing the τ(φ)-hypothesis is meagre (Wann 1996). Most studies did not consider violations of the τ(φ)-hypothesis; rather, the goal of this research was to confirm that observers relied on τ(φ). For example, in some studies participants performed the interception task under binocular viewing, but the discussions of these experiments focused entirely on the monocular variable τ(φ) (cf. van der Kamp et al. 1997).

Recent research almost unambiguously refutes the tau-hypothesis because the predictions stemming from the sole exploitation of the relative rate of expansion are violated (cf. Tresilian 1999). Many psychophysical studies showed that perceptual judgments of time were affected by the speed of approach (e.g. McLeod and Ross 1983; Schiff et al. 1992; Sideway et al. 1996) and the size of objects (e.g. DeLucia 1991; DeLucia and Warren 1994; Heuer 1993). The time-to-contact was judged shorter for larger and faster approaching objects. Similar effects are also found for interceptive actions in a more natural setting. Interceptive actions are initiated at a shorter time before contact with a higher movement velocity to faster approaching balls (e.g. Montagne et al. 2000; Bennett et al. 1999; Mason and Carnahan 1999; Wallace et al. 1992; Smeets and Brenner 1995) and larger object sizes (Michaels et al. 2001; van der Kamp et al. 1997). Since the value of τ(φ) is invariant over changes in speed and size, the observed results are qualitatively more consistent with a strategy based on alternative optical variables.

It was Schiff who first pointed at the absolute rate of expansion (i.e $\dot{\varphi}$; see Fig. 1) in the regulation of timing (Schiff 1965; Schiff et al. 1962). He showed that different animal species showed avoidance reactions when confronted with optical expansion patterns. Initiation on basis of a critical value of the absolute rate of expansion predicts that movements are initiated later for both faster and larger approaching balls. Recently, Michaels et al. (2001) attempted to push this qualitative agreement into a quantitative one. They performed an experiment in which participants had to punch balls of different diameter falling from different heights, under both monocular and binocular conditions. The results showed a main effect of ball size for elbow flexion and an interaction effect of viewing by ball size for elbow extension. The extensions were initiated at the same time for small and large balls in the binocular condition, whereas in the monocular condition the extension to the large ball was earlier than to the small ball. This suggests that different variables may be exploited in the monocular and binocular condition. Quantitative analyses revealed a critical value for optical expansion velocity to initiate flexion of the arm (first phase). The optical variable that regulated the initiation of extension of the arm (second phase) was less conclusive since different variables [including the (relative) rate of expansion] were exploited by different participants. Although quantitative evidence is still scarce, the initiation of interceptive actions seems to be more consistent with a regulation based on the absolute rate of expansion than the relative rate of expansion [i.e. τ(φ)].

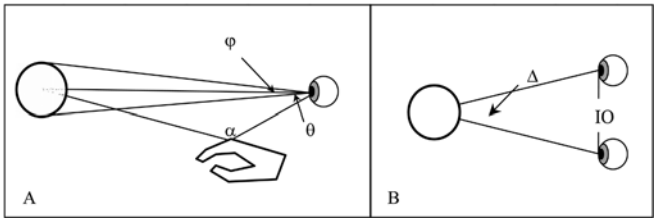

Fig. 1 A A ball approaching on a collision course with the eye. The angle subtended between the point of observation and the ball is φ, the angle between the hand, the point of observation and the ball is θ, and the angle between the point of observation, the hand and the ball is α. **B** In binocular vision, the distance between the eyes is the interocular distance (*IO*), and the angle between the two eyes and the ball is denoted Δ

Except for the meagre quantitative evidence, another concern with the above-described research may be the assumption that only a single source of information is used for the temporal control of all interceptive actions (cf. Caljouw et al. 2004a). However, task constraints may impose boundaries on the effectiveness of certain optical sources. An example of a flexible attunement to optical variables depending on specific properties of the task environment was given by Smith et al. (2001). They aimed at uncovering whether participants relied on $\dot{\varphi}$ or τ(φ) when releasing a virtual pendulum so that it collided at its vertical position with an approaching ball. Smith et al. (2001) showed that at the beginning of the experiment participants used a rate of expansion strategy resulting in consistently missed collisions. However, at the end of the experiment participants made the collisions, and the data showed that a combination of expansion rate and optical angle was involved. Note that the combination of the two optical variables was different from that predicted on the basis of τ(φ), although it may indicate that participants were adapting more and more towards a tau strategy. Hence, the authors stated that optical angle and rate of expansion contribute independently, and that they can be combined depending on the accuracy demands of a task[2].

In catching, alternatives to monocular expansion sources, such as binocular variables and variables that are correlated to the "closure of the gap" between hand and ball may be involved as well. Our view is that the many different sources that are available, and in some sense co-vary with the approach of the ball, may or may not be used to regulate interceptive actions depending on the task at hand. An optical source that takes into account the point of interception may be essential to accurately regulate catching. Optical "gap" variables such as the rate of constriction (i.e. $\dot{\theta}$; see Fig. 1), or the relative rate of constriction of the specified gap between the hand and the ball [i.e. τ(θ)] are defined such that both points of observation and interception are incorporated. Bootsma and Oudejans (1993) provided evidence for participants'

[2] Note that the optical variable η, which has received some attention in the perception of collisions as well (Sun and Frost 1998; López-Moliner and Bonnet 2002), is also a joint function of optical angle and rate of expansion.

sensitivity to the relative rate of constriction of the gap combined with the relative rate of expansion [i.e. $\tau(\varphi,\theta)$] in the perception of time-to-collision between a ball and a stationary target. Also, an experiment in which participants had to trap balls rolling down a trackway indicated that participants did not exclusively rely on information limited to the expansion pattern generated by the trajectory of the ball (Tresilian 1994). It is noteworthy that both studies only considered outcome measurements (i.e. percentage of correct judgements and number of timing errors, respectively). So, it remains to be tested whether $\dot{\theta}$ and $\tau(\theta)$ could actually be involved in anticipatory timing; more detailed quantitative analyses are requisite.

Besides monocular information sources, also binocular information may contribute to the timing of one-handed catching. Van der Kamp et al. (1997) reported that hand closure was affected by ball size under monocular viewing, but not under binocular viewing (see also Michaels et al. 2001). This confirms the proposition that binocular information, such as the relative rate of disparity [i.e. $\tau(\Delta)$] is involved in interceptive actions (Laurent et al. 1996). However, the timing of hand closure was also affected when the interocular separation was increased (Bennett et al. 1999, 2000; van der Kamp et al. 1999). This suggests that the absolute rate of disparity, rather than the relative rate of disparity, is involved. Unfortunately, quantitative evaluations have been restricted to monocular variables such as $\dot{\varphi}$ and $\tau(\varphi)$; the contribution of binocular variables in interceptive actions has never been investigated quantitatively. The described qualitative results show that the temporal aspects of catching are not solely regulated on the basis of a monocular optical variable when participants view the scene with two eyes. Even when binocular information is misleading, in case of a disrupted interocular separation, it is still not neglected or ignored. Obviously, monocular catches can only be guided by monocular information. In contrast, binocular catches can be regulated on the basis of either monocular or binocular information alone, or on binocular and monocular information together. Regan and Beverly (1979) proposed that the relative importance of monocular (i.e. rate of expansion) and binocular information (i.e. rate of disparity) is equal to twice the ratio of the object diameter (R) and the interocular separation (IO). Since this ratio is independent of approach velocity, no differences between monocular and binocular vision for balls approaching with different velocity would be expected. Bennett et al. (1999; 2000) endorsed this proposition, since they did not find any interaction effects between viewing condition and approach speed, but did show a mediating effect of object size on the contribution of binocular information. However, empirical evidence for the influence of vision in relation to approach speed is still ambiguous. On the one hand, Regan et al. (1979) showed that with increasing speed binocular information about motion in depth becomes more effective relative to monocular information. On the other hand, Cavallo and Laurent (1988) reported the opposite; they found a higher accuracy in the estimation of time-to-collision for binocular than for monocular vision for slower speeds only.

Finally, Wann (1996) proposed that the temporal aspect of interceptive actions may be controlled based on a distance ratio (denoted ζ) instead of time-related variables. The relative distance from the point of observation, i.e. D/D_{start} (D_{start} is the distance at the instant the ball first becomes visible), was thought to be invariant at the moment of movement initiation (see also Wallace et al. 1992). The use of the relative distance ratio is consistent with observing an earlier initiation for slower approaching balls. However, a potential disadvantage is that the ratio does not predict differences in movement initiation for approaching balls of different size.

The purpose of the present experiment is (1) to settle the issue whether the initiation of a one-handed catch is dependent on object speed and viewing, and (2) to evaluate the explanatory value of various information sources including the relative distance ratio and optical variables such as $\dot{\varphi}$, $\dot{\theta}$, $\dot{\Delta}$, $\tau(\varphi)$, $\tau(\theta)$, $\tau(\Delta)$, and $\tau(\theta,\varphi)$. The fact that we generally don't know*how* an optical variable constrains a movement, poses a serious difficulty in determining *what* optical variables are used. In order to relate the optical variables to the kinematics of a movement we have to assume a lawful relationship between the structure of light and the movements of an observer, i.e. a control law (see Warren 1988). A proposed strategy is that a critical value of an optical variable is used to trigger the initiation of a movement. A critical timing strategy is often associated with the predictive operational timing strategy of Tyldesley and Whiting (1975) in which an estimate of the remaining time-to-contact is used to trigger a pre-planned movement of a fixed duration (Fitch and Turvey 1978). There is evidence for the existence of invariable movement times especially in highly practiced actions (Hubbard and Seng 1954; Franks et al. 1985; Wollstein and Abernethy 1988), but predictive strategies are in general inflexible and computationally burdensome. Under task constraints of actions like catching and hitting, performers are typically able to continuously regulate the movement by viewing the ball until it arrives at the location of the hand (Bootsma and Van Wieringen 1990; Savelsbergh et al. 1991). A close and continuous coupling of movement and perceptual systems can be founded on the relationship between the instantaneous states of the performer and the environment during task performance. An important attempt to formalise the relationship has been made by the required velocity model (Peper et al. 1994) and its extensions (Bootsma et al. 1997; Montagne et al. 2000; Dessing et al. 2002). Unfortunately, continuous modelling often starts after the initiation of the movement, so most continuous control models do not explain systematic initiation patterns as abundantly in the literature. It is however, important to note that continuous controlled actions should still be initiated and that continuous control does not exclude triggering on the basis of a critical value. This perspective on information–movement coupling shifts the attention from a perceptual

account based on the estimation of time-to-contact and the triggering of a movement programme with a fixed duration to a dynamical account based on continuous coupling of movement (including the moment of initiation) to information. However, it remains to be established on which optical information the initiation and subsequent control is based.

If participants use a threshold value of the absolute rate of change of an optical angle instead of the relative rate of change for the initiation of an interceptive movement, the timing will relate to ball approach speed. For example, for fast approaching objects the absolute rate of change of expansion (i.e.$\dot{\varphi}$) increases sharply and suddenly over the last portion of the travelled distance, whereas for slowly approaching objects the increase in angular rate is more gradual (cf. Fig. 2). Considering the time-evolution of $\dot{\varphi}$ for the different ball speeds, we would predict that the initiation of the reach will occur earlier before contact for slower moving balls. Furthermore, we would expect that the magnitude of the difference between successive approach speeds for movement onset will decrease with ball speed. It is, however, much harder to predict beforehand the effects originating from regulation on basis of the rate of change of "gap" variables (i.e. $\dot{\theta}$, $\tau(\theta)$, since the time-evolutions of these variables do not depend solely on the approach of the ball but also on the position and velocity of the hand towards the ball.

To identify the information used to regulate the timing of initiation, we will first analyse the relationship between event variables (speed, viewing) and the kinematics of the catch. Second, we will quantitatively assess the relationship between the relative distance ratio and movement onset patterns. Finally, the explanatory value of an initiation based on a critical value of $\dot{\varphi}$, $\dot{\theta}$, $\dot{\Delta}$, $\tau(\varphi)$, $\tau(\theta)$, $\tau(\Delta)$, or $\tau(\theta, \varphi)$ will be evaluated based on direct measurements of these optical variables. Based upon a critical triggering strategy, we expect the values of the variable used at onset of movement to be the same, i.e. the values of the optical variable used should be independent of ball velocity at a particular visuomotor interval before movement onset.

Methods

Participants

Six women and two men 20–38 years of age (averaged age 26.4 years) participated voluntarily in this experiment. They all reported normal or corrected-to-normal vision and had stereoscopic vision in the normal range with assessed stereoacuity of at least 40 seconds of arc as determined with by the stereopsis test (Titmus Optical Inc., Petersburg, VA, USA). All participants were unaware of the purpose of the experiment. This study is part of an ongoing research programme that has been approved by the institutional ethics committee. Before testing began, the experiment was explained and the participants gave their consent to participate. One participant was excluded from data analyses because she often obstructed the ball-marker with her hand during the catch. As a consequence, the moment of ball–hand contact and the position of ball–hand contact could barely be discerned. In the end, data from seven participants were analysed.

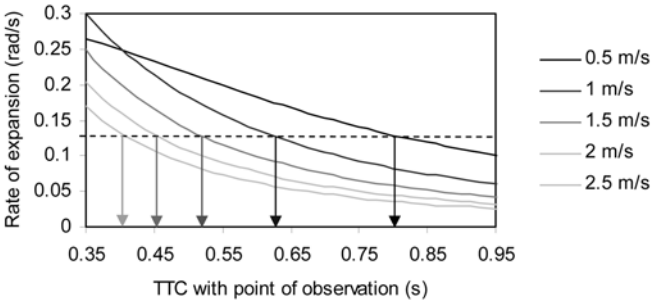

Fig. 2 The time-evolution of the rate of expansion for five approach speeds of the ball (i.e. 0.5, 1, 1.5, 2 and 2.5 m/s). The point of observation was assumed to be located 20 cm to the left of the ball path. *Horizontal dashed line*represents the hypothesised critical value and*vertical arrows* depict the matching time-to-contact (TTC) for each ball speed. A critical value of about 0.13 rad/s is reached at a smaller TTC with the point of observation for faster approaching balls. This would result in an earlier initiation for the approach speed of 2.5 m/s than for the 0.5-m/s condition

Task and apparatus

The participants' task was to catch a ball (6 cm in diameter), while sitting upright. The ball approached with a fixed spatial trajectory on one of five constant velocities (0.5, 1.0, 1.5, 2.0, 2.5 m/s). The height-adjustable seat was positioned so that the balls were transported at eye height next to the participant's right shoulder (about 20 cm from the right eye). At the start of each trial, the participants had to place their forearm on a table (height 76 cm) in a fixed position, with the elbow against an armrest (see Fig. 3). They were instructed to keep their thumb in contact with their index finger. No further instructions were given on how to reach for and grasp the ball. To perform a successful catch, the participants needed to regulate temporal as well as the spatial characteristics of the catching hand, because they were free to choose the position at which the ball was caught along the sagittal axis.

The balls were presented using the Ball Transport Apparatus (BallTrAp; Fig. 3). The BallTrAp consists of a large wooden box (305×110×15 cm) containing two aluminium wheels, the centres of which are 210 cm apart and connected to each other by a rubber belt. One wheel was driven by a Micron MT30r4-58 Servo motor. Fixed to the belt was a little trolley with an aluminium rod. The ball was connected to the rod through an air-circuit that reduced pressure in the rod, so that the ball was held in place by suction. The position of the ball was 50 cm above the initial position of the hand. The ball was accelerated to a constant velocity before it became visible at a distance of 220 cm. We did not manipulate the viewing distance, since a preliminary experiment on one-handed catching showed no significant effect of viewing distance on the moments of initiation (van der Kamp 1999). When the participant caught the ball, it released from the rod. The rod, however, moved on, guaranteeing constant velocity at the moment of ball-hand contact. To reduce the noise of the BallTrAp, music was played to the participant through a set of headphones.

To isolate the information sources we performed the experiments in a completely darkened room. During a trial, only the ball and the participant's right hand were visible. The balls were transparent and attached to a small light that was placed in the tube of the suction system. The hand was covered with a tight glove, which was covered with luminescent paint. Before each trial a strong lamp was used to activate the luminescent paint.

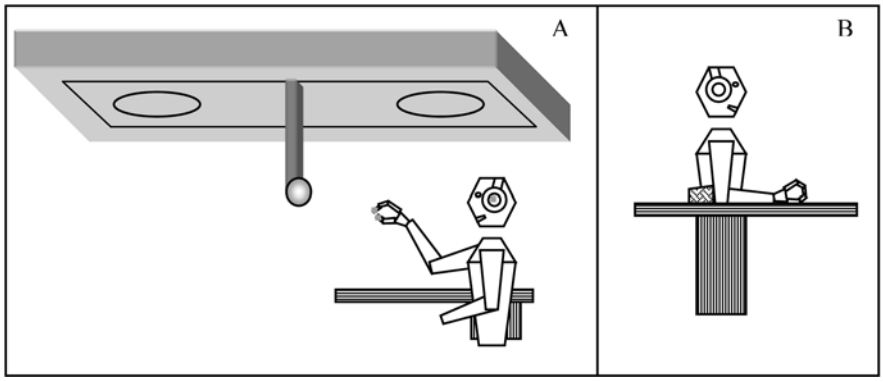

Fig. 3 **A** Side view of the ball transport (BallTrAp) system. The participant was seated at the end of the 2.20-m straight path of the track. The ball was transported at eye height to the right side of the participant. The *light grey squares* on the fingers and on the headphone illustrate the position of the infrared-emitting diodes. **B** Side view of the initial position of the right arm. The elbow rests against an armrest, which is fixed to the table. The thumb is held in contact with the index finger

Procedure and design

Before the experiment started, the participants were allowed to perform practice trials to become familiar with the experiment. The participants received 15 practice trials at different velocities. The practice trials were performed with lights on and binocular viewing.

During the experiment, each participant performed one block of trials with monocular viewing and one block with binocular viewing. One half of the participants started with monocular viewing and the other half with binocular viewing. In the monocular conditions, the right eye was covered with an eye-patch. In the two 'viewing' blocks, five constant velocities were presented (0.5, 1.0, 1.5, 2.0, and 2.5 m/s). Each block consisted of 50 randomly ordered trials, ten at each velocity. The experiment took approximately 1 h, with a break of about 5 min after 50 trials.

Dependent variables and data analyses

A 3-D-motion analysis system (one Optotrak camera unit with a sampling rate of 200 Hz; Northern Digital, Waterloo, ON, Canada) registered the catch with an accuracy of 0.2 mm. The positions of four infra-red light-emitting diodes (IREDs) were acquired. The IREDs were fixed to the first phalanx of the thumb and index finger, the left side of the headphones, and to the ball. The 3-D positions of the IREDs were filtered with a second-order recursive Butterworth low-pass filter, with a cutoff frequency of 10 Hz.

The exact position and time of ball–hand contact were determined by the sampled position data of the ball. The moment of ball–hand contact was defined as the moment at which the ball profile deviated from its linear pattern. Subsequently, the trajectory of the ball was extrapolated according to a first-order polynomial fit. The moment of intersection between ball and eye plane was defined as time zero. The exact point of observation was reconstructed from the IRED located at the left side of the headphones.

Apart from the number of catching failures, the analysis of the data consisted of two parts. First, the kinematic properties of reaching and grasping movements were calculated from the position profiles from the thumb and index finger. To determine the kinematics of the reach, the sampled position data of the thumb and index finger were averaged. Seven dependent variables were calculated. Note that, all temporal measures were defined with respect to the time to intersection between the ball and the eye plane. These were:

1. Moment of reach onset (the time at which the averaged thumb and index finger approached the object with 5% of the peak reach velocity)
2. Peak reach velocity (the maximum velocity attained by the averaged thumb and index finger)
3. Moment of peak reach velocity (the time at which the peak reach velocity occurred)
4. Moment of hand closure (the time at which the distance between thumb and index finger started to decrease with 5% of the peak closing velocity)
5. Peak closing velocity (maximum closing velocity between thumb and index finger)
6. Maximum hand aperture (the maximum distance between the thumb and index finger)
7. Position of ball–hand contact (the position at which the ball is caught relative to the initial position of the hand)

The second part of the analyses consisted of a quantitative assessment of the ratio D/D_{start} and of several optical variables to determine whether the use of particular variables to initiate the reach or hand closure might be excluded. For each trial we determined the distance between the ball and the start position of the hand at the moment of reach onset and hand closure (D). We related this distance to the initial distance (D_{start}) at which the ball became visible, i.e. 2 m away from the start position of the hand. We did not take the visuomotor interval into account. This was considered to be justified because the incorporation would have resulted in an even larger difference between the ratios at onset for the different approach speeds (see the Results section).

The problem that arose when assessing the other optical variables quantitatively is that we knew neither the critical values of the informational variables nor the time it took for the information to affect the movement of the effector. We tackled this problem by means of a method first presented by Michaels et al. (2001) in their punching ball study (for a similar account see also Caljouw et al. 2004b). Since there is no a priori reason to assume that the participants exploited similar critical values of the optical variables and matching visuomotor intervals, each participant had to be considered individually. First, the values of the optical angles were computed using the 3-D position profiles from the ball, the head and the averaged position of thumb and index finger. Phi (i.e. φ, the angle subtended between the right eye and the edges of the ball), theta (i.e. θ, the angle subtended between the effector, the right eye, and the centre of the ball), and in the binocular condition, delta (i.e. Δ, the angle between the centre of the ball and the two eyes) were calculated for each trial at the moment of reach onset and hand closure. By differentiating the optical angles, $\dot{\varphi}$, $\dot{\theta}$, $\dot{\Delta}$ were determined. Subsequently, the tau-functions were calculated by dividing the optical angle by its rate of change. The optical variable $\tau(\varphi,\theta)$ was calculated by taking the inverse of $\tau(\varphi)^{-1}-\tau(\theta)^{-1}$. This variable specifies time-to-interception, assuming that the interception point is fixed. In the present experiment the time to interception is affected by motion of the ball as well as motion of the hand. So, the relative rate of constriction of the gap between hand and ball does not depend solely on ball motion. A variable that precisely specifies time-to-interception, should include the angle subtended

between the point of observation, the hand, and the centre of the ball (i.e. α; cf. Fig. 1), besides θ and φ. We did not analyse this compound variable since our focus is on optical variables and the angle α is not directly available to the visual system[3].

One cannot expect the values of the optical variables used at onset of the movement to be the same; assuming a constant visuomotor interval over trials with different ball speeds, they would only converge at a point in the past equal to this visuomotor interval. Therefore, the values of all these different optical sources were calculated at different visuomotor intervals before onset of the reach and hand closure, ranging from 50 to 300 ms, using intermediate steps of 10 ms. This was done for each trial. Finally, for each optical variable, at each visuomotor interval, simple regression analyses were conducted to establish the correlation between the optical values and ball velocity. If, for example, $\dot{\varphi}$ is the variable on basis of which the initiation of the reach is controlled, then it ought to be the case that the values of $\dot{\varphi}$ at this particular point in time should be independent of ball velocity. In other words, a critical value is discerned when the regression between the informational value and the ball approach velocity for that particular visuomotor interval should result in a r^2close or equal to zero. Interpretation of a low value ofr^2 is difficult because it may indicate a zero slope of the regression line or it may indicate that the majority of the variability of the optical variable is not explained by the different approach velocities. Therefore, except for a low regression coefficient, we introduced an additional criterion that the coefficient of variation, which is the ratio of the standard deviation over the mean value (e.g. Wagner 1982; Bootsma and Van Wieringen 1990), may not exceed the 30%. Furthermore, a value is only qualified as critical if the matching visuomotor interval of the minimum non-significant regression coefficient was found to be smaller than 275 ms. An optical variable with a visuomotor interval larger than 275 ms cannot account for initiation, because the critical value than occurred at a time before the ball was visible, especially in conditions where the ball was arriving fast.

Results

Both the number of balls missed and the intra-subject means and standard deviations of all dependent variables were calculated for each condition and submitted to a 2×5 [viewing (monocular versus binocular) × velocity (0.5, 1.0, 1.5, 2.0 and 2.5 m/s)] analysis of variance with individual repeated-measures on both factors (ANOVA). In the case that the sphericity assumption was violated (i.e. $\varepsilon<1.0$), Huyn-Feldt adjustments of the*P*-values are reported. Post hoc comparisons were conducted with Tukey's HSD test ($P<0.05$). Because the results were roughly similar and usually reflected by the group averages, only the statistics of the group data will be described.

[3] We investigated whether information sources alone could account for the observed timing of onset patterns, which does of course not exclude the possibility that a regulation based on combinations of information sources may be consistent with our data as well (e.g. Smith et al. 2001; López-Moliner and Bonnet 2002). In the present experiment we cannot falsify such a regulation based on combinations of information sources since the optical variables can be combined with scaling parameters in infinite ways.

Catching failures

Only 18 out of 700 balls were not caught. Most of the misses (i.e. six) occurred in the 2.5-m/s condition under monocular viewing, but the ANOVA did not reveal any significant effects.

Effects of viewing

Table 1presents the group means and average within-subject standard deviations of all kinematic dependent variables. Although this table suggests that monocular viewing resulted in higher peak reach velocities, there was no significant effect of viewing on any of the peak velocities. The timing parameters of the catch were affected by viewing. The reach onset ($F_{(1,6)}=12.63$, $P<0.05$) and the moment of hand closure ($F_{(1,6)}=15.93$, $P<0.01$) under monocular viewing occurred at significantly shorter time before contact with the eye plane. An interaction effect of viewing × speed ($F_{(4,24)}=3.55$, $P<0.05$) was present for the reach onset, indicating that the viewing effect was modulated by velocity. Tukey's comparisons showed that the influence of viewing was restricted to the two lowest velocities. If the timing is significantly different under monocular viewing but peak velocity is not, we would expect to find differences in the position of ball–hand contact. Indeed, ANOVA revealed that participants caught the ball significantly nearer to them while viewing the scene with one eye ($F_{(1,7)}=14,03$, $P<0.005$). The maximal hand aperture was independent of viewing condition. Also, the mean intra-subject standard deviations did not show any effects related to viewing condition.

Effects of ball velocity

Increasing the ball velocity clearly affected the timing of the catch. Significant main effects of velocity were found for the onset of the reach ($F_{(4,24)}=135.50$, $P<0.001$), the moment of peak reach velocity ($F_{(4,24)}=212.00$, $P<0.001$), and the moment of hand closure ($F_{(4,24)}=393.43$, $P<0.001$). With increasing speed, all temporal parameters occurred closer to the moment of intersection of the ball with the eye plane, as can be seen in Table 1. This was affirmed by Tukey's comparisons. With respect to the intra-subject standard deviations, significant effects of velocity were found for the onset of the reach ($F_{(4,24)}=11.15$, $P<0.001$), the moment of peak reach velocity ($F_{(4,24)}=10.37$, $P<0.005$) and the moment of hand closure ($F_{(4,24)}=16,59$, $P<0.005$). Post hoc tests indicated that the standard deviations pertaining to the temporal parameters were larger for the two lowest ball speeds than for the two highest ball speeds.

The peak velocities of the reach and the hand closure also depended on ball approach speed ($F_{(4,24)}=56.83$ and$F_{(4,24)}=69.74$, respectively, both $P<.001$): the faster the ball, the higher the movement velocity. In addition, ball

Table 1 Means and standard deviations of all dependent variables for the binocular and monocular viewing group as a function of ball velocity (0.5, 1, 1.5, 2 and 2.5 m/s). The moments of reach onset, peak reach velocity and hand closure are expressed in seconds before ball intersection with the eye plane. The catch position is relative to the initial position of the hand

Variable	Statistic	Monocular viewing					Binocular viewing				
		0.5 m/s	1 m/s	1.5 m/s	2 m/s	2.5 m/s	0.5 m/s	1 m/s	1.5 m/s	2 m/s	2.5 m/s
Moment of reach onset (s)	Mean	−1.47	−0.90	−0.74	−0.63	−0.49	−1.53	−0.99	−0.75	−0.64	−0.53
	SD	0.17	0.09	0.10	0.06	0.04	0.17	0.13	0.06	0.07	0.04
Moment of peak reach velocity (s)	Mean	−1.19	−0.67	−0.53	−0.45	−0.33	−1.27	−0.73	−0.55	−0.47	−0.37
	SD	0.13	0.07	0.09	0.06	0.03	0.16	0.13	0.06	0.07	0.04
Moment of hand closure (s)	Mean	−0.83	−0.39	−0.28	−0.22	−0.17	−0.89	−0.43	−0.30	−0.23	−0.18
	SD	0.08	0.04	0.04	0.03	0.02	0.11	0.04	0.03	0.02	0.02
Peak reach velocity (mm/s)	Mean	1448	1681	1785	1929	2226	1406	1516	1718	1853	2148
	SD	196	208	223	233	251	151	197	201	228	297
Peak closing velocity (mm/s)	Mean	−372	−574	−768	−905	−1080	−440	−619	−766	−897	−1043
	SD	86	108	147	144	163	92	102	102	152	174
Maximal hand aperture (mm)	Mean	110	114	117	120	122	113	117	121	120	123
	SD	5	4	5	5	4	5	5	4	5	4
Catch position (mm)	Mean	52	14	13	17	−9	83	47	39	39	24
	SD	45	35	40	35	28	38	32	29	34	31

speed had a significant effect on the maximal hand aperture ($F_{(4,24)}$=22.18, P<0.001) and the position at which the ball was caught ($F_{(4,24)}$=14.03, P<0.005). Post hoc tests showed, first, that participants opened their hand to a larger extent while catching balls approaching at the two lowest velocities than those approaching at the two highest velocities, and, second, that the ball was caught further from the initial position of the hand when the ball approached at 0.5 m/s.

With respect to the mean intra-subject standard deviations, ANOVA revealed that the standard deviations of peak reach velocity ($F_{(4,24)}$=3.80, P<0.05) and peak closing velocity ($F_{(4,24)}$=6.64, P<0.005) depended on ball speed. In contrast with the standard deviations of the temporal parameters, post hoc tests indicated that the standard deviations attained for the lowest velocity were significantly smaller than for the highest velocity. Standard deviations of maximal hand aperture and catching position were not significantly different among the different ball speeds.

The relative distance ratio and optical variables

Table 2 shows the values of D/D_{start}. ANOVA revealed a significant effect of ball speed on the ratios D/D_{start} at both reach onset ($F_{(4,24)}$=153.5, P<0.001) and hand closure ($F_{(4,24)}$=6.4, P<0.005). The post hoc tests showed that the ratio increased with each increase in ball speed, except for ball speeds 2 and 2.5 m/s.

This suggest that the percentage of the distance travelled by the ball at the moment of reach onset decreased with increasing ball speed. The effect of ball approach speed on the distance ratio showed a different pattern for the moment of hand closure. Post hoc tests revealed that only the ratio found for the 2-m/s condition differed significantly from the other ball speed conditions. Furthermore, a significant interaction effect was found ($F_{(4,24)}$=2.9, P<0.05) between ball speed and viewing. Indicating that for the moment of hand closure the ratio found in the 2-m/

Table 2 Means and standard deviations of the relative distance ratios at the moments of reach onset and hand closure as a function of ball speed and viewing

Viewing	Ball speed (m/s)	Onset reach		Hand closure	
		Mean	SD	Mean	SD
Monocular	0.5	0.22	0.04	0.06	0.02
	1.0	0.31	0.06	0.05	0.02
	1.5	0.41	0.07	0.07	0.03
	2.0	0.5	0.07	0.08	0.03
	2.5	0.49	0.06	0.06	0.02
Binocular	0.5	0.23	0.06	0.07	0.02
	1.0	0.34	0.08	0.07	0.02
	1.5	0.41	0.08	0.08	0.02
	2.0	0.5	0.1	0.08	0.02
	2.5	0.52	0.11	0.08	0.02

s trials differed from all other ball speed conditions under monocular viewing, but only differed from the 1-m/s condition under binocular viewing. Taking into account the significant effects of ball speed on both reach onset and hand closure, we conclude that the observed timing patterns are not consistent with an invariant relative distance ratio.

Figure 4shows the regression coefficients of the simple regressions between the values of $\tau(\varphi)$, $\tau(\theta)$, $\dot{\varphi}$, $\dot{\theta}$ and ball approach velocity for one participant. The data presented are for the reach onset (Fig. 4A) and hand closure (Fig. 4B) of participant 1 in the monocular condition. The regression coefficients are plotted as a function of the visuomotor interval. As can be seen, a local minimum was found in the regressions for $\tau(\theta)$, $\dot{\theta}$, and $\dot{\varphi}$ at reach onset. That is, the regression coefficient for these optical variables are close to zero at a particular visuomotor interval: 260 ms for $\dot{\varphi}$, 270 ms for $\tau(\theta)$ and 330 ms for $\dot{\theta}$. Note, however, that an optical variable is probably not involved when the matching visuomotor interval is larger than 275 ms (see Methods section). For hand closure, critical values could be discerned for $\tau(\theta)$ and $\dot{\theta}$, with matching visuomotor intervals of 100 and 230 ms, respectively. Table 3 shows for all participants the minimum non-significant regression coefficients between ball approach velocity and the values of $\tau(\varphi)$, $\tau(\theta)$, $\tau(\theta, \varphi)$, $\dot{\varphi}$, $\dot{\theta}$ and, in addition, for the binocular condition $\tau(\Delta)$ and $\dot{\Delta}$. Where the coefficient of variation of a particular variable exceeded the 30% level (*asterisks* in Table 3), the inference of a critical value became less reliable.

Three findings, presented in Table 3, deserve close attention. First, for reach onset and hand closure no critical values could be discerned for optical variables that specify first-order time-to-contact [i.e. $\tau(\varphi)$ and $\tau(\Delta)$]. This was already indicated by the observed velocity effects on the temporal parameters of the kinematics. Second, for hand closure, no critical values could be found for optical variables solely confined to the trajectory of the ball [i.e. $\tau(\varphi)$, $\tau(\Delta)$, $\dot{\varphi}$, $\dot{\Delta}$]. Only variables that are related to the closure of the gap between hand and ball contribute to the timing of hand closure [i.e. $\tau(\theta)$, $\tau(\theta,\varphi)$, $\dot{\theta}$]. Third, the analysed binocular variables [i.e. $\tau(\Delta)$, $\dot{\Delta}$] could not be shown to regulate the timing. Low regression coefficients with binocular variables were found for reach onset, but they occurred mainly at visuomotor intervals larger than 275 ms. It seems unlikely that $\tau(\Delta)$ and $\dot{\Delta}$contribute to the regulation of the reach onset, since binocular information is most salient when the object is within arm reach (Collewijn and Erkelens 1990). This finding has also gained support in interceptive studies, for example in the work of Bennett et al.(2000) who showed that the telestereoscope (i.e. a device that increases the interocular separation) did influence the initiation of hand closure, but not the initiation of hand opening in one-handed catching. Note, however, that the contribution of other binocular variables to regulate hand closure, such as binocular variables related to the closure of the gap, cannot, of course, be ruled out on basis of these findings.

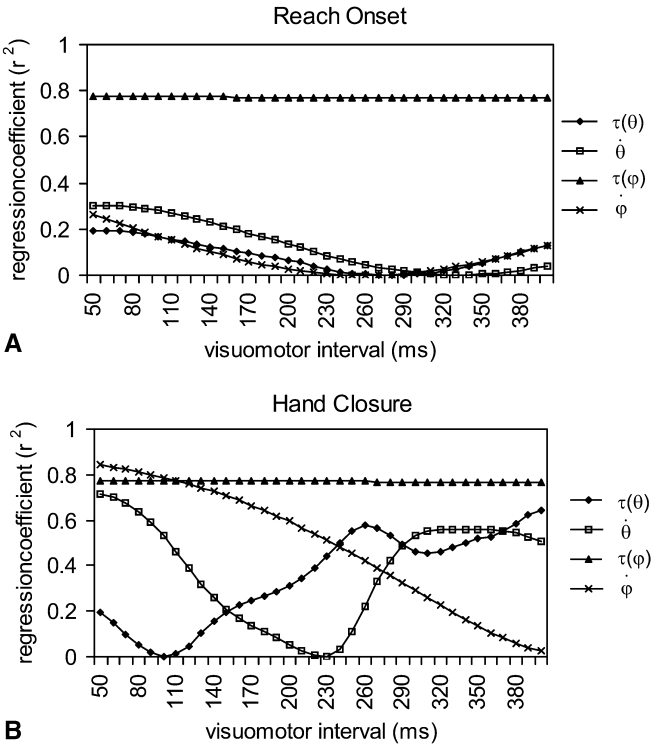

Fig. 4A,B Coefficients of the regressions between four informational variables and ball approach velocity for a visuomotor interval of 0 to 400 ms for reach onset (**A**) and hand closure (**B**) of participant 1

Discussion

The aim of the present experiment was first, to qualitatively investigate the relation between event variables (i.e. ball speed and viewing) and the kinematics of the catch, and subsequently to directly assess quantitatively the relation between optical variables and the observed timing patterns.

Effects of ball speed on the kinematics of the catch

Several adaptations of the catch were observed when the approach speed of the ball increased. First, peak velocity of the reach and hand closure were found to increase with increasing ball speed. Second, the maximum hand aperture increased. Third, the position of ball–hand contact was closer to the observation point. Finally, all temporal parameters (i.e. onset of the reach and hand closure, moment of peak reach velocity) occurred closer to the moment of intersection with the eye plane.

With respect to the first observation, speed coupling is a persistent phenomenon in different interceptive actions (Smeets and Brenner 1995; Brouwer et al. 2000; Carnahan

Table 3 Minimum non-significant regression coefficients and matching visuomotor intervals (ms) for the regressions between the informational variables and ball approach velocity at reach onset and hand closure, for binocular and monocular catches (*s* significant regression)

Viewing	Subject	Parameter	Reach onset							Hand closure						
			$\tau(\varphi)$	$\tau(\varphi,\theta)$	$\tau(\Delta)$	$\tau(\theta)$	$\dot{\varphi}$	$\dot{\Delta}$	$\dot{\theta}$	$\tau(\varphi)$	$\tau(\varphi,\theta)$	$\tau(\Delta)$	$\tau(\theta)$	$\dot{\varphi}$	$\dot{\Delta}$	$\dot{\theta}$
Monocular	1	Regression coefficient	s	s	–	0.000	0.001	–	s	s	0.001	–	0.000	s	–	0.003
		Visuomotor interval				270	260				260		100			230
	2	Regression coefficient	s	s	–	0.001	0.000	–	0.000	s	0.001	–	0.002*	s	–	0.005*
		Visuomotor interval				190	260		240		260		90			230
	3	Regression coefficient	s	s	–	0.000*	s	–	s	s	0.000	–	0.000	s	–	0.001
		Visuomotor interval				60					200		60			270
	4	Regression coefficient	s	s	–	0.000	0.001	–	0.000	s	0.001	–	0.053*	s	–	0.038
		Visuomotor interval				170	250		220		160		120			180
	5	Regression coefficient	s	s	–	0.000	0.000	–	s	s	0.001*	–	0.000*	s	–	0.000
		Visuomotor interval				230	260				270		210			250
	6	Regression coefficient	s	s	–	0.001	s	–	s	s	0.000*	–	s	s	–	0.001*
		Visuomotor interval				220					190					240
	7	Regression coefficient	s	s	–	0.000*	s	–	s	s	0.001	–	0.000*	s	–	0.003
		Visuomotor interval				230					210		140			230
Binocular	1	Regression coefficient	s	s	s	0.000	0.000	0.000	0.002	s	0.001	s	s	s	s	0.002
		Visuomotor interval				200	210	270	270		240					200
	2	Regression coefficient	s	s	s	0.000*	0.001	s	0.000	s	0.000	s	0.000*	s	s	0.000
		Visuomotor interval				170	250		190		230		80			220
	3	Regression coefficient	s	s	s	s	s	s	s	s	s	s	0.000	s	s	s
		Visuomotor interval											240			
	4	Regression coefficient	s	s	s	0.000	0.000	s	s	s	0.001	s	s	s	s	0.000
		Visuomotor interval				190	250				60					100
	5	Regression coefficient	s	s	s	s	s	s	0.011*	s	0.000*	s	s	s	s	0.000
		Visuomotor interval							250		130					240
	6	Regression coefficient	s	s	s	s	s	s	s	s	0.001	s	s	s	s	0.004
		Visuomotor interval									170					240
	7	Regression coefficient	s	s	s	0.001	s	s	s	s	0.000*	s	0.000*	s	s	0.027
		Visuomotor interval				240					200		100			240

*Coefficient of variation of that particular variable exceeded the 30% level

and McFayden 1996; Dubrowski and Carnahan 2001; Tresilian and Lonergan 2002; Tresilian et al. 2003); for example Smeets and Brenner (1995) showed speed-coupling in spite of the instruction to hit their running spiders as hard and quickly as possible. Different suggestions were made in order to explain why people move faster to faster approaching objects. An explanation that fits our data well is based on accuracy demands (Brouwer et al. 2000; Tresilian and Lonergan 2002; Tresilian et al. 2003). A ball is within reach for a shorter period when it approaches with a high velocity, and it is this time window that defines the temporal precision required to perform the task. If the time window is small, the temporal precision has to be high. A way in which people cope with this demand of increased temporal precision might be by increasing their movement velocity (Schmidt 1982). In the present experiment, it was indeed observed that the variability of the timing decreased with increasing ball speed. So, it might be that the participants exploited the greater precision of rapid movements to make accurate interceptions within narrow time limits. Besides increasing the movement velocity, participants also opened their hand to a wider extent (see also Mason and Carnahan 1999) and caught the ball closer to the point of observation (see also Chieffi et al. 1992). Both adaptations might be exploited by the participants in order to increase the time window. By increasing the hand aperture people introduced a larger margin of safety (Wing et al. 1986), and catching the ball closer to the point of observation resulted in extra time available to perform the interception (Laurent et al. 1994).

The approach speed has an additional effect on timing. The moments of initiation, i.e. initiation of the reach and hand closure, occurred significantly longer before intersection of the ball with the eye plane in response to slower approaching objects. From these qualitative results, we can only conclude that the averaged timing pattern of moments of initiation is not in agreement with an initiation based on a threshold value of optical variables specifying the time of passage (Bootsma and Craig 2002), i.e. the time it takes the ball to cross the eye plane. In order to identify the optical variables that may have been used in timing the initiation of catching movements we analysed the data quantitatively.

The optical variables that quantitatively predict the observed results

We aimed at uncovering the optical variables involved in the timing of the reach and grasp in one-handed catching. Previous research cast doubts on the actual involvement of $\tau(\varphi)$ in the regulation of interceptive actions. In the present experiment we examined the merits of several alternative variables. The quantitative analyses showed that the results were not in agreement with the initiation of a movement on basis of optical variables specifying the time-to-contact with the point of observation, i.e. $\tau(\varphi)$ and $\tau(\Delta)$. The ball-speed effects on the timing of reach onset were qualitatively consistent with a regulation based on the relative distance ratio, $\dot{\varphi}$ and $\dot{\Delta}$. The common prediction of these invariants is an initiation at a shorter time before ball–eye intersection at increased velocity. However, quantitatively, the observed timing patterns of hand closure and reach onset were found to contradict the relative distance hypothesis of Wann (1996). Instead of an invariant ratio over trials, the relative distance was found to vary systematically with ball approach speed. The variable $\dot{\varphi}$ has gained some support in previous studies where approach velocity and size were varied (Michaels et al. 2001; Smith et al. 2001). However, determination of the critical values in our experiment only yielded positive results for reach onset in four participants. For none of the seven participants was a critical value of $\dot{\varphi}$ discerned for the moment of hand closure. If we assume that only one optical variable is used to regulate both reach onset and hand closure, we have to rule out $\dot{\varphi}$, since this variable produced positive results for reach onset, but not for hand closure. Note that the same holds true for the optical variable $\tau(\theta,\varphi)$ yielding positive results for hand closure, but not for reach onset.

If we accept that participants are able to treat different variables as separate degrees of freedom that can be used alone or in combination to regulate the action (e.g. Cutting 1986; Laurent et al. 1996), we may be forced to conclude that participants use variables depending on the task constraints. The present results suggest that the dominance of information related to the closure of the "gap" between end-effector and ball increases with approach, since $\tau(\theta, \varphi)$ contributes to the regulation of hand closure, and not to the reach onset. The only variables for which critical values could be discerned for both reach onset and hand closure were $\dot{\theta}$ and $\tau(\theta)$. Note that in the present experiment the optical variables $\tau(\theta)$ and $\tau(\theta,\varphi)$ do not specify the time-to-interception between the ball and the end-effector. The optical variable $\tau(\theta,\varphi)$ only specifies the TTC_1 of a moving object with a stationary interception point (or target), and $\tau(\theta)$ specifies the TTC_1 between a moving object and a stationary interception point as long as the physical gap between the object and the target is perpendicular to the line of sight. So, participants relied neither on perceived TTC_1 with the point of observation nor on TTC_1 with the point of interception. So far the discussed variables have been defined monocularly. However, the results showed that binocular catches were significantly different from monocular catches. The binocular catches were initiated earlier (i.e. at a longer time before contact) and this effect was most pronounced for the two lowest velocities. The examined binocular variables $\tau(\Delta)$ and $\dot{\Delta}$, however, did not yield any positive results, and only one critical value could be found for $\dot{\Delta}$(viz. for reach onset in one participant). This seems peculiar since $\dot{\Delta}$is temporally congruent with the monocular variable $\dot{\varphi}$ that did yield positive results for reach onset in four participants. However, the kinematic analyses showed that the binocular catches occurred at a

longer time before contact and the balls are caught further from the point of observation. Therefore, critical values of $\dot{\Delta}$were found before the ball was visible for many trials (especially for the fast approach conditions). As binocular information becomes more salient with the approach of the object (Collewijn and Erkelens 1990), it seems unlikely that this optical variable is exploited to regulate reach onset (see also Bennett et al. 2000). Participants, however, might have exploited binocular "gap" variables to regulate hand closure. The precise form of a binocular variable that is congruent to the absolute rate of constriction of the gap is yet unknown. Moreover, empirical research showed that binocular and monocular information is not used in isolation, but rather in combination (Gray and Regan 1998; Smith et al. 2001; van der Kamp et al. 1999). In the present analysis we only investigated a critical strategy based on the exploitation of a single optical variable to regulate initiation. As Smith et al. (2001) argued, optical variables might be viewed as independent dimensions in an optical state space and combining them might result in flexible attunements to different task constraints. The challenge for future research into the regulation of interceptive actions, both as it concerns initiation and continuous control, is to answer how the different optical variables combine to regulate the timing.

For many years the search for optical variables was constrained by information specifying TTC_1. This was due to the implicit reasoning that the detection of information about an event entails the perception of this event, and that it is the perception of this event that regulates the action. However, the optical information for the perception of the time-to-contact of an approaching ball, may be different from the optical information used to regulate the timing of a movement (cf. Milner and Goodale 1995; Michaels 2000; van der Kamp et al. 2001). As shown in the present experiment, actors do not always rely on perceived TTC to time the movement initiation. Other optical sources may be used to trigger the initiation of a movement, followed by parameterisation or continuous guidance of the interceptive movement. The present observations stress the point that, in the information-based regulation of interceptive timing, subjects exploit information that is defined over both the approaching object and the end-effector. This conclusion is in agreement with Bootsma and Oudejans (1993) and Tresilian (1994) who both emphasised the importance of the interception point. However, their formulations are characterised by the explicit search for variables that specify TTC. The present experiment indicates that information solely confined to the trajectory of the ball (i.e. the absolute rate of expansion) might be used to regulate the timing of the reach onset, but not the timing of hand closure. Only variables that are to some extent related to the closure of the gap between hand and ball were found to contribute to the timing of hand closure. This suggests that information related to the constriction of the optical gap between end-effector and ball becomes more important with approach, whereas the contribution of the absolute rate of expansion becomes less leading.

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